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Determination of Precise Satellite Orbits and Geodetic Parameters using Satellite Laser Ranging

Public defense of the doctoral dissertation

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Table of contents

Three Pillars of Satellite Geodesy

Geometry

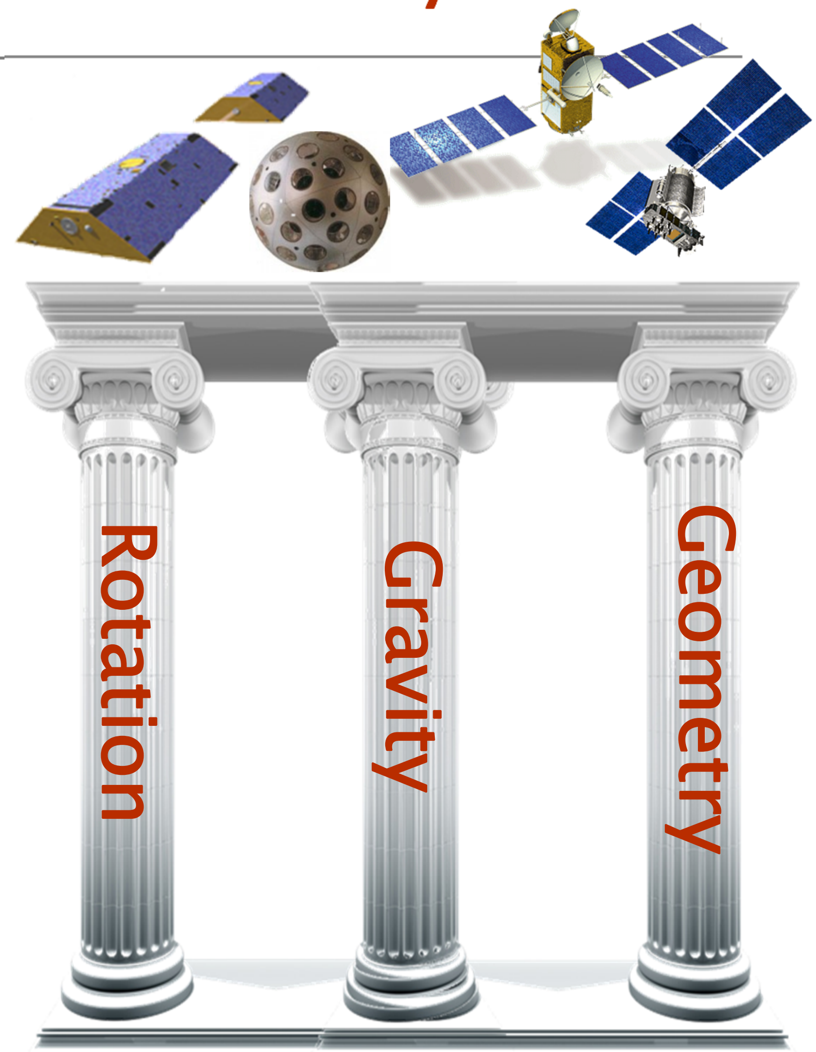
Determination of geometrical three-dimensional positions and velocities (in global, regional, and local reference frames),

Gravity

Determination of the Earth's gravity field and its temporal variations,

Rotation

Modeling and observing of geodynamical phenomena (tectonic plates, loading crustal deformations) including the rotation and orientation of the Earth (polar motion, Length-of-day, precession and nutation).



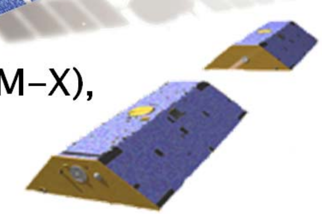
Satellite Geodesy

Observation Techniques in Satellite Geodesy

Satellite and space observation techniques contributing to the Global Geodetic Observing System (GGOS):

- Techniques used for the definition of the International Terrestrial Reference Frame (ITRF) :
  - Global Navigation Satellite Systems (GNSS, e.g., GPS, GLONASS, Galileo, Beidou),
  - Very Long Baseline Interferometry (VLBI),
  - Doppler Orbitography and Radiopositioning Integrated by Satellite (Détermination d'Orbite et Radiopositionnement Intégré par Satellite, DORIS),
  - Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR).

- Other techniques of satellite geodesy:
  - Satellite altimetry (e.g., TOPEX-Poseidon, Jason-1/2),
  - Interferometric Synthetic Aperture Radar (InSAR), e.g., TerraSar-X, TanDEM-X),
  - Satellite gravimetry (e.g., GRACE, GRAIL, GOCE),
  - Satellite optical imagery,
  - Other remote sensing techniques (e.g., geomagnetic field mapping, e.g., SWARM).

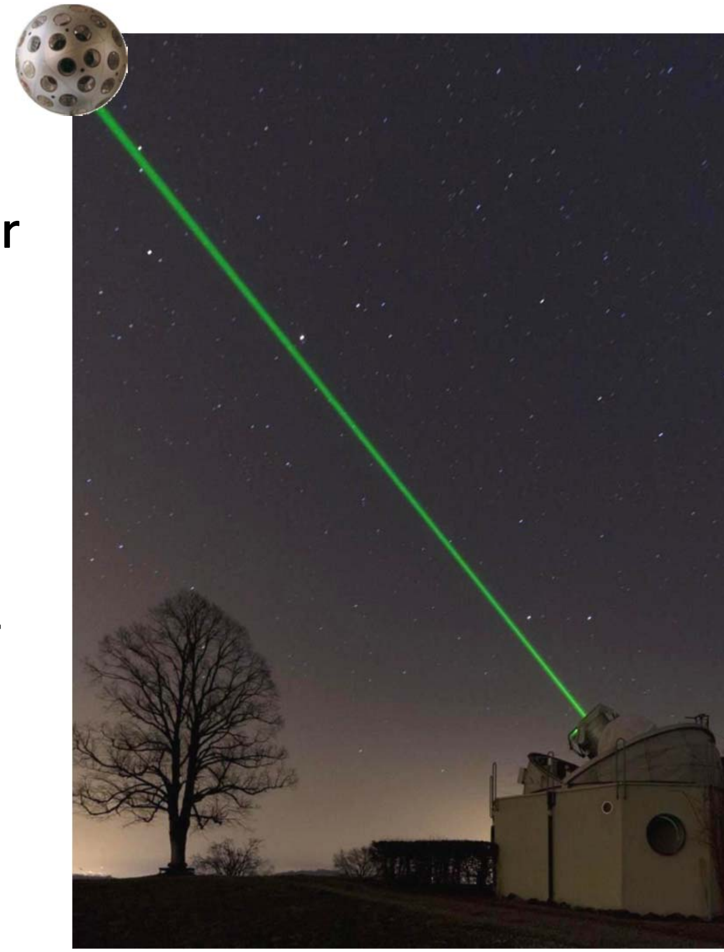


Satellite Laser Ranging (SLR)

SLR is one of the space-geodetic techniques used for precise positioning, for determination of Earth's gravity field, and for measurement of geodynamical phenomena.

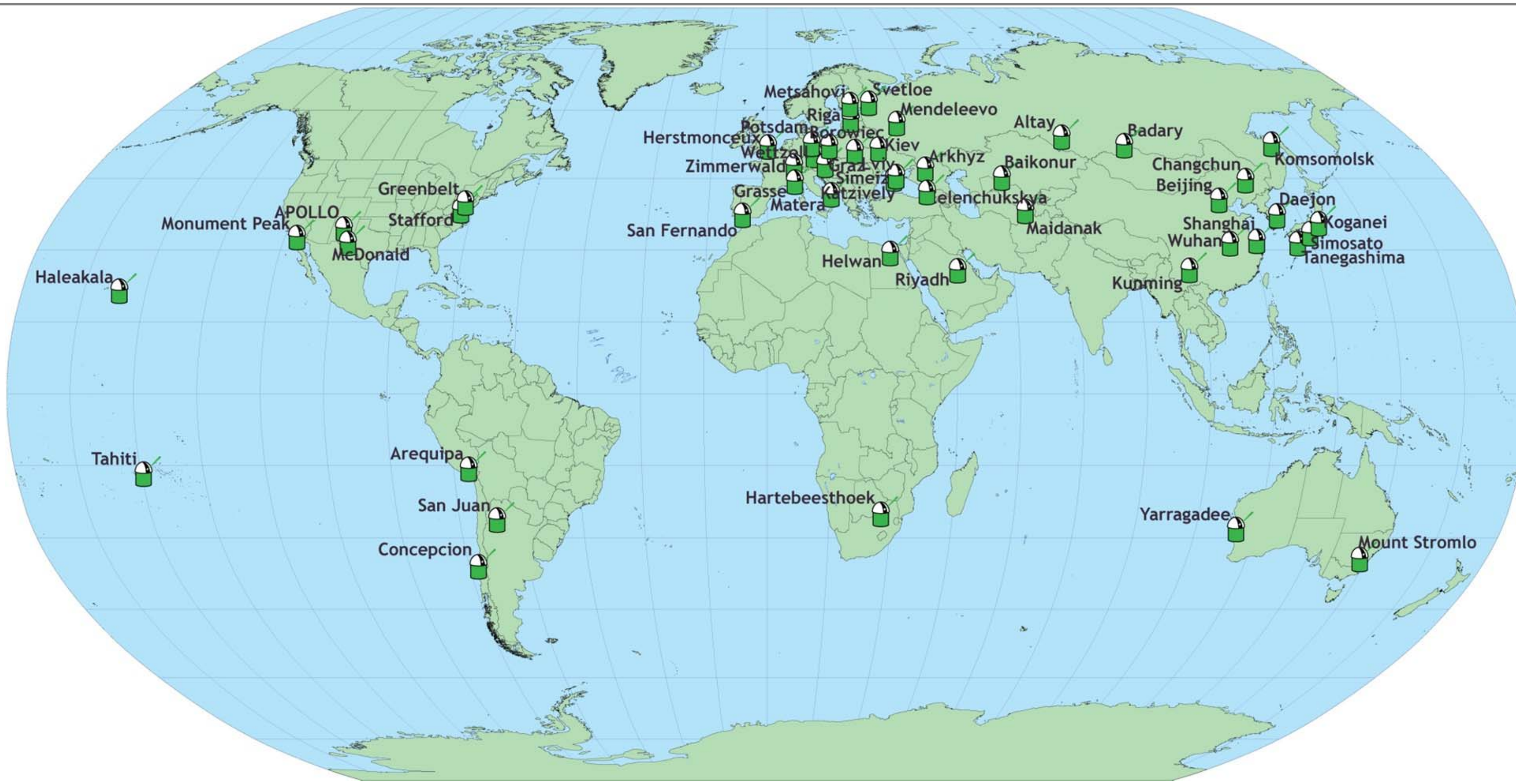
In SLR the basic observable is the two-way travel time of a laser pulse between a ground station and a satellite. The time of flight can be transformed into a direct distance by multiplying the time of flight of a laser pulse by the velocity of light.

$$\Delta t_r^s = \frac{2}{c}(d_r^s + \delta_{tro} + \delta_{rel}) + \frac{1}{c}\delta_{sys} + \epsilon_{tr}^s,$$



The Zimmerwald Observatory

International Laser Ranging Service (ILRS)

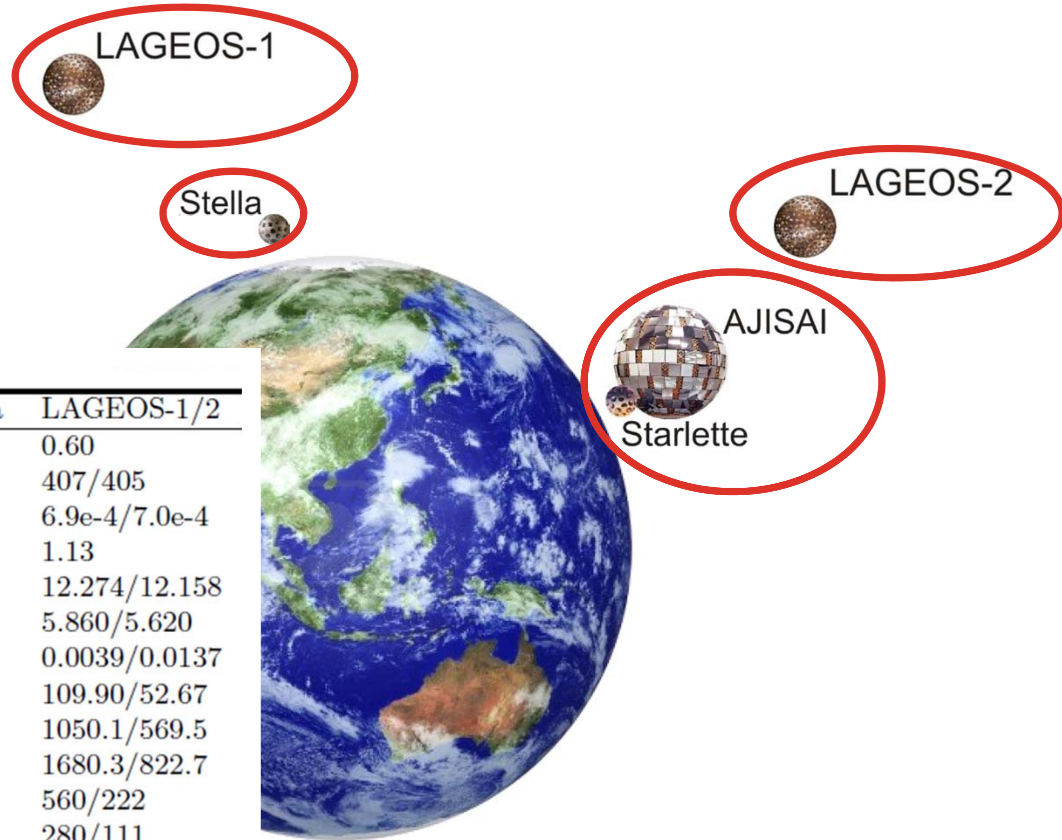


The International Laser Ranging Service (ILRS) coordinates all operational and scientific activities of the institutions involved in scientific lunar and satellite laser ranging since 1998.
The ILRS provides official products primarily based on SLR observations to the spherical geodetic satellites: LAGEOS-1/2 and Etalon-1/2. The official ILRS products are based on 7-day solutions and consist of station coordinates, polar motion, and length-of-day parameters.

Geodetic SLR Satellites

Current ILRS products:

- Based on LAGEOS-1/2 & Etalon-1/2 solutions only,
- On average ~3000 normal points to LAGEOS-1/2 and ~300 normal points to Etalon-1/2 per week,
- The impact of Etalon-1/2 on the solution is virtually negligible



	AJISAI	Starlette/Stella	LAGEOS-1/2
Diameter [m]	2.15	0.24	0.60
Mass [kg]	685	47/48	407/405
Area-to-mass [m^2kg^{-1}]	58.0e-4	9.6e-4/9.4e-4	6.9e-4/7.0e-4
Radiation coeff. C_R	1.03	1.134/1.131	1.13
Semi-major axis [km]	7.866	7.335/7.176	12.274/12.158
Orbit altitude [km]	1.500	800-1.100/830	5.860/5.620
Eccentricity	0.0016	0.0205/0.0010	0.0039/0.0137
Inclination [deg]	50.04	49.84/98.57	109.90/52.67
Drift of node [days]	116.77	90.97/364.7	1050.1/569.5
Drift of perigee [days]	141.1	108.7/122	1680.3/822.7
Draconitic year [days]	89	72.8/182	560/222
S_2 alias period [days]	44.5	36.5/91	280/111
A priori CoM corr.	1010 mm	78 mm	CoM[1]

[1] station-specific CoM (Appleby et al. 2012)

List of Parameters in 7-day SLR Solutions

Parameter		LAGEOS	LEO
Station Coordinates		Weekly	Weekly
Earth Rotation Parameters		PWL daily	PWL daily
Geocenter Coordinates		Weekly	Weekly
Gravity field		Up to d/o 4	Up to d/o 4
Range Biases		**Selected stations**	**All stations**
Orbit	Osculating Elements	Weekly	Weekly
	Constant along-track S0	**Weekly**	-
	Air Drag Scaling Factor	-	**Daily**
	Once-per-rev SS, SC	**Weekly**	**Daily**
	Once-per-rev WS, WC	**Weekly** (when not estimating gravity field)	**Daily**
	Pseudo-Stochastic Pulses	-	**Once-per-rev in along-track**

Bernese GNSS Software, v.5.3

Precise Orbit Determination of SLR Satellites

Satellite Perturbing Forces

Perturbing accel.	Accel. on LAGEOS	Accel. on AJISAI	Accel. on LARES	Accel. on Stella
Gravitational perturbations:				
· Earth's monopole	2.7	6.4	6.5	7.7
· Earth's oblateness $C_{2\,0}$	$1.0 \cdot 10^{-3}$	$6.2 \cdot 10^{-3}$	$6.3 \cdot 10^{-3}$	$8.8 \cdot 10^{-3}$
· Low-order grav. $C_{2\,2}$	$6.0 \cdot 10^{-6}$	$3.6 \cdot 10^{-5}$	$3.7 \cdot 10^{-5}$	$5.1 \cdot 10^{-5}$
· Low-order grav. $C_{6\,6}$	$8.6 \cdot 10^{-8}$	$3.1 \cdot 10^{-6}$	$3.2 \cdot 10^{-6}$	$6.3 \cdot 10^{-6}$
· Mid-order grav. $C_{20\,20}$	$8.1 \cdot 10^{-13}$	$1.5 \cdot 10^{-8}$	$1.6 \cdot 10^{-8}$	$1.1 \cdot 10^{-7}$
· Grav. attr. of Moon	$2.1 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$	$1.3 \cdot 10^{-6}$
· Grav. attr. of Sun	$9.6 \cdot 10^{-7}$	$6.4 \cdot 10^{-7}$	$6.5 \cdot 10^{-7}$	$5.7 \cdot 10^{-7}$
· Grav. attr. of Venus	$1.3 \cdot 10^{-10}$	$8.5 \cdot 10^{-11}$	$8.5 \cdot 10^{-11}$	$7.8 \cdot 10^{-11}$
· Solid Earth tides	$3.7 \cdot 10^{-6}$	$2.0 \cdot 10^{-5}$	$2.0 \cdot 10^{-5}$	$2.9 \cdot 10^{-5}$
· Ocean tides	$3.7 \cdot 10^{-7}$	$1.9 \cdot 10^{-6}$	$2.0 \cdot 10^{-6}$	$3.0 \cdot 10^{-6}$
General relativity:				
· Schwarzschild effect	$2.8 \cdot 10^{-9}$	$1.1 \cdot 10^{-8}$	$1.1 \cdot 10^{-8}$	$1.4 \cdot 10^{-8}$
· Lense-Thirring effect	$2.7 \cdot 10^{-11}$	$1.3 \cdot 10^{-10}$	$1.4 \cdot 10^{-10}$	$1.8 \cdot 10^{-10}$
· Geodetic precession	$3.4 \cdot 10^{-11}$	$4.2 \cdot 10^{-11}$	$4.2 \cdot 10^{-11}$	$4.3 \cdot 10^{-11}$
Non-gravitational perturbations:				
· Solar radiation pressure	$3.5 \cdot 10^{-9}$	$2.5 \cdot 10^{-8}$	$1.1 \cdot 10^{-9}$	$4.4 \cdot 10^{-9}$
· Earth radiation pressure	$4.4 \cdot 10^{-10}$	$8.6 \cdot 10^{-9}$	$3.9 \cdot 10^{-10}$	$1.8 \cdot 10^{-9}$
· Thermal re-radiation	$5.0 \cdot 10^{-11}$	$4.1 \cdot 10^{-10}$	$1.9 \cdot 10^{-11}$	$6.9 \cdot 10^{-11}$
· Light aberration	$1.1 \cdot 10^{-13}$	$1.1 \cdot 10^{-12}$	$5.1 \cdot 10^{-14}$	$2.0 \cdot 10^{-13}$
· Atmospheric drag (~ min)	$0.8 \cdot 10^{-14}$	$3.0 \cdot 10^{-11}$	$2.6 \cdot 10^{-12}$	$5.0 \cdot 10^{-11}$
· Atmospheric drag (~ max)	$2.0 \cdot 10^{-13}$	$5.9 \cdot 10^{-10}$	$4.8 \cdot 10^{-11}$	$5.0 \cdot 10^{-8}$

AJISAI:

- Diameter: 2.15 m
- Mass: 685 kg
- Area-to-mass: A/m: $58 \cdot 10^{-4}$ m² kg⁻¹

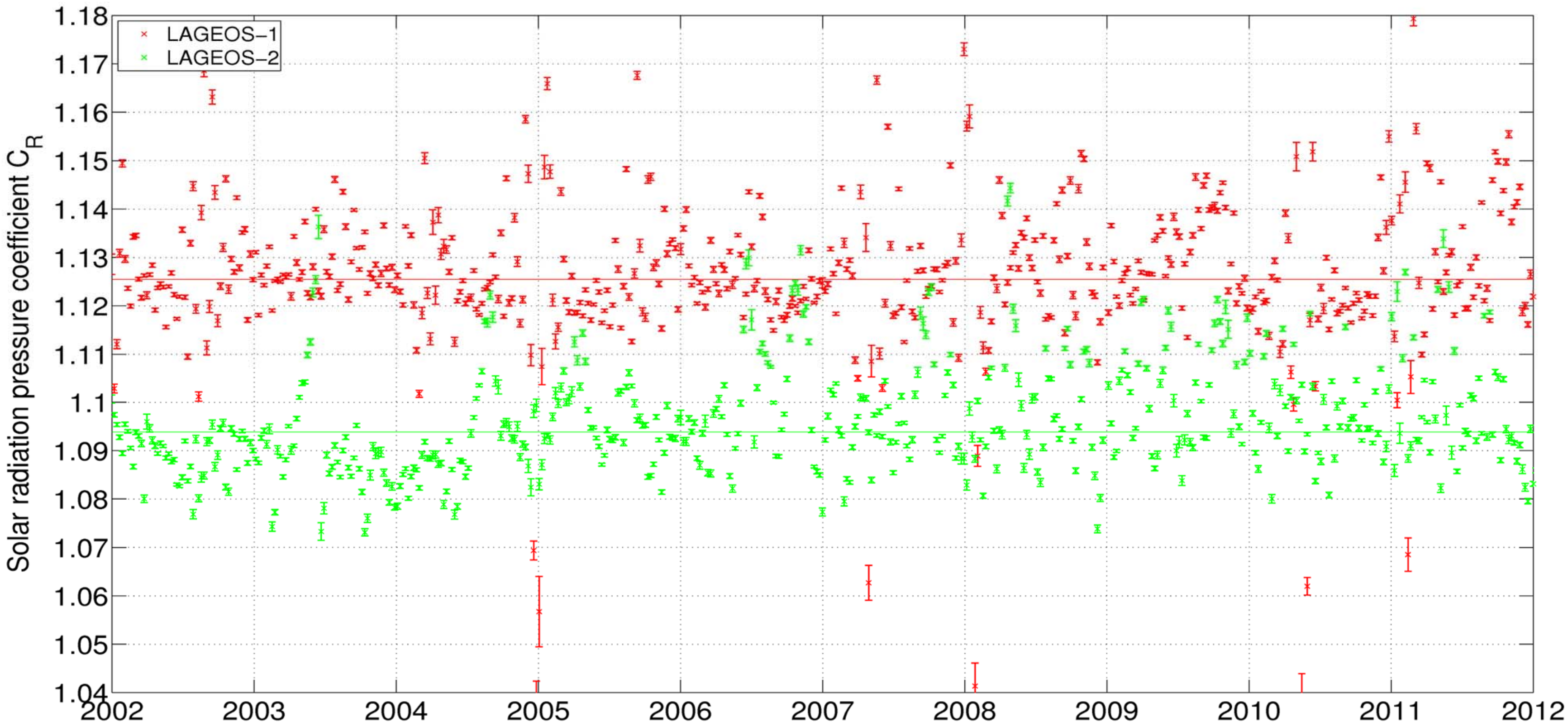
LAGEOS:

- Diameter: 0.60 m
- Mass: 407 kg
- Area-to-mass: A/m: $6.9 \cdot 10^{-4}$ m² kg⁻¹

LARES:

- Diameter: 0.36 m
- Mass: 387 kg
- Area-to-mass: A/m: $2.7 \cdot 10^{-4}$ m² kg⁻¹

Solar Radiation Pressure



Standard value of the solar radiation pressure coeff. used by most ILRS ACs:

- C_R = 1.13 for LAGEOS-1 & LAGEOS-2

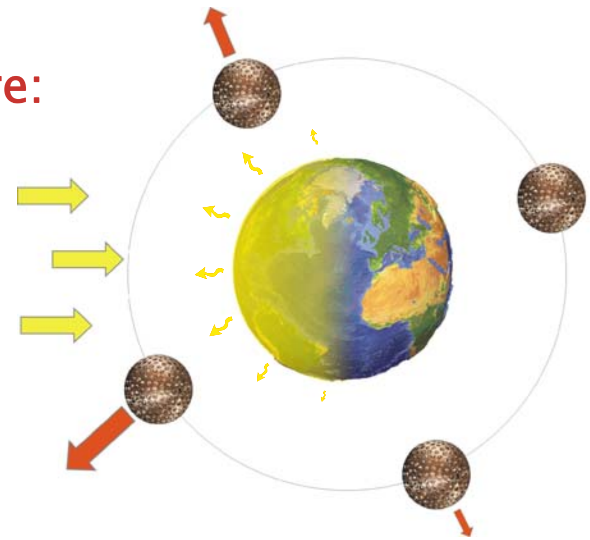
From this study:

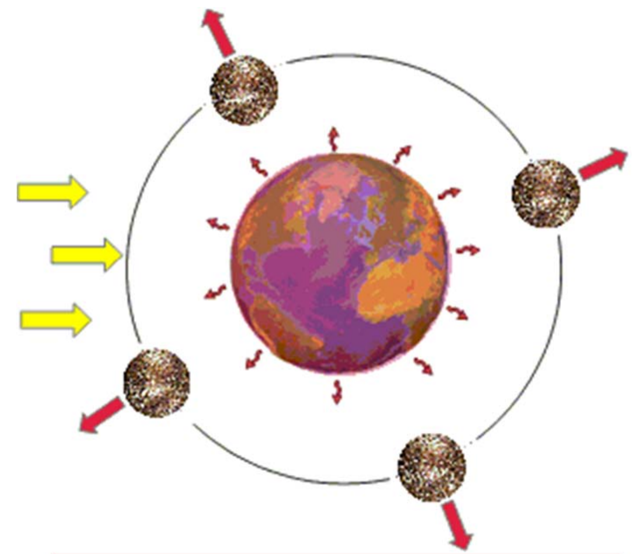
- C_R = 1.125 ± 0.015 for LAGEOS-1
- C_R = 1.094 ± 0.012 for LAGEOS-2

Albedo

Earth Radiation Pressure:

- Visible Earth's reflectivity
- Infrared Earth's emissivity

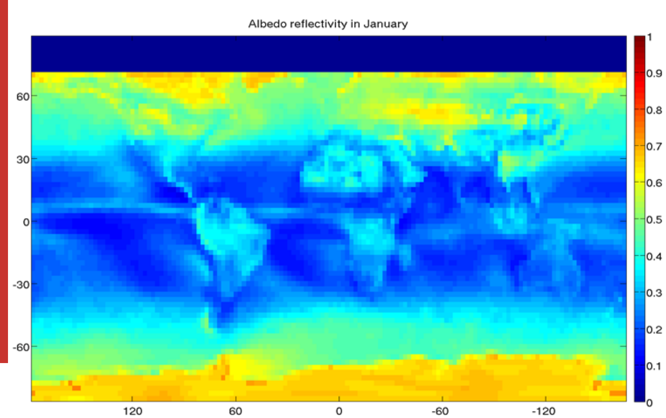




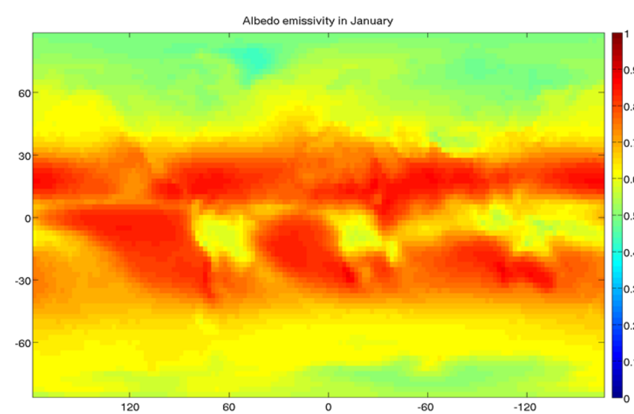
The Earth emissivity renders about 60% of total albedo effect and introduces a rather constant force in the radial direction.

Source of data: monthly global maps from the CERES mission, grids 2.5x2.5 (Rodriguez-Solano et al., 2011)

Reflectivity



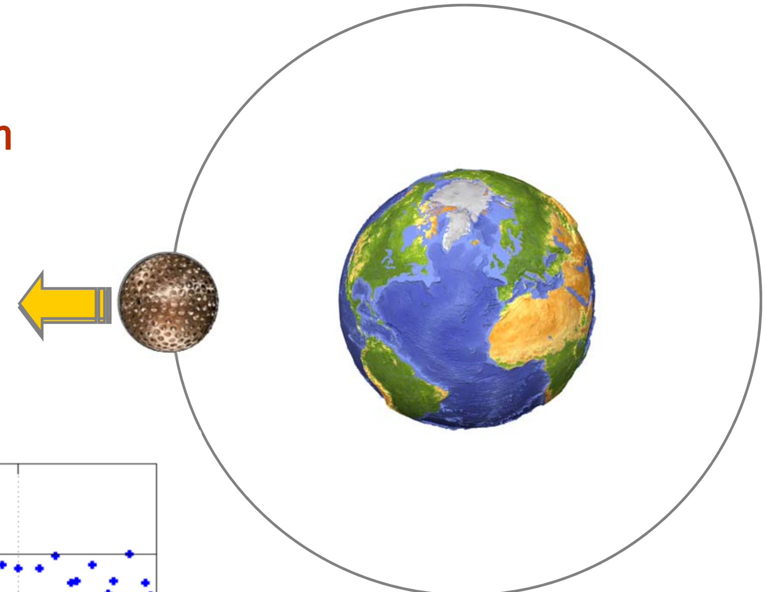
Emissivity

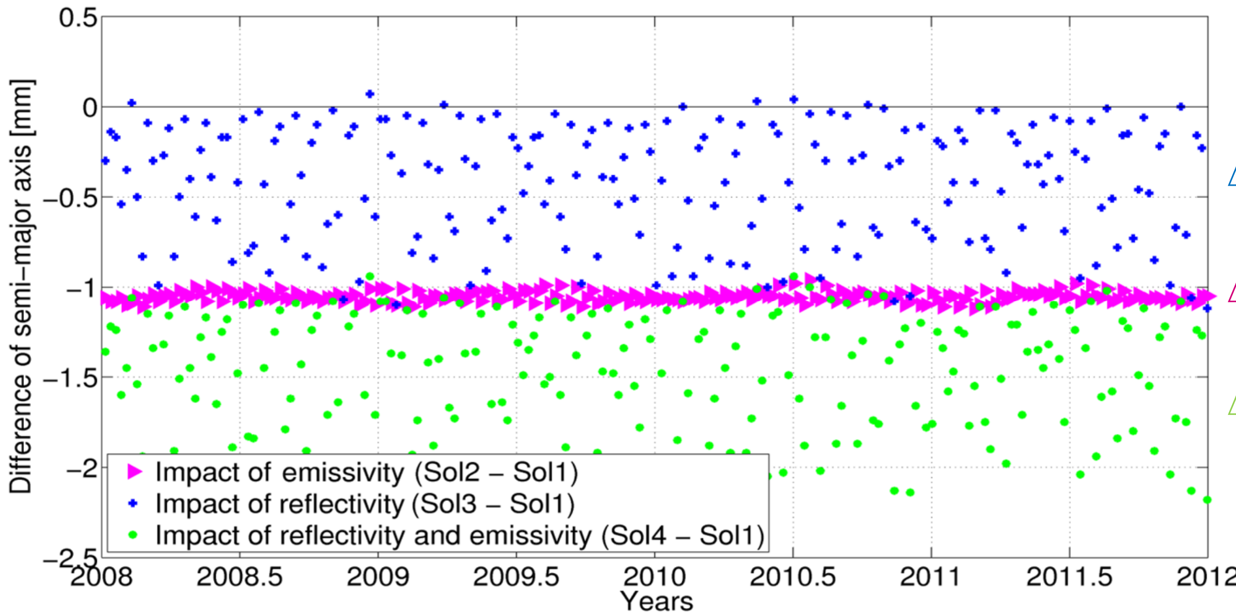


Albedo – impact on LAGEOS orbits

A difference in the estimated semi-major axis *a* when introducing an additional constant force in the radial direction R_0 can be expressed as:

$$\Delta a = -\frac{4}{3}\frac{a^3 R_0}{GM}.$$





Δa = -0.5 mm due to refl.

Δa = -1.0 mm due to emiss.

Δa = -1.5 mm due to refl+emiss.

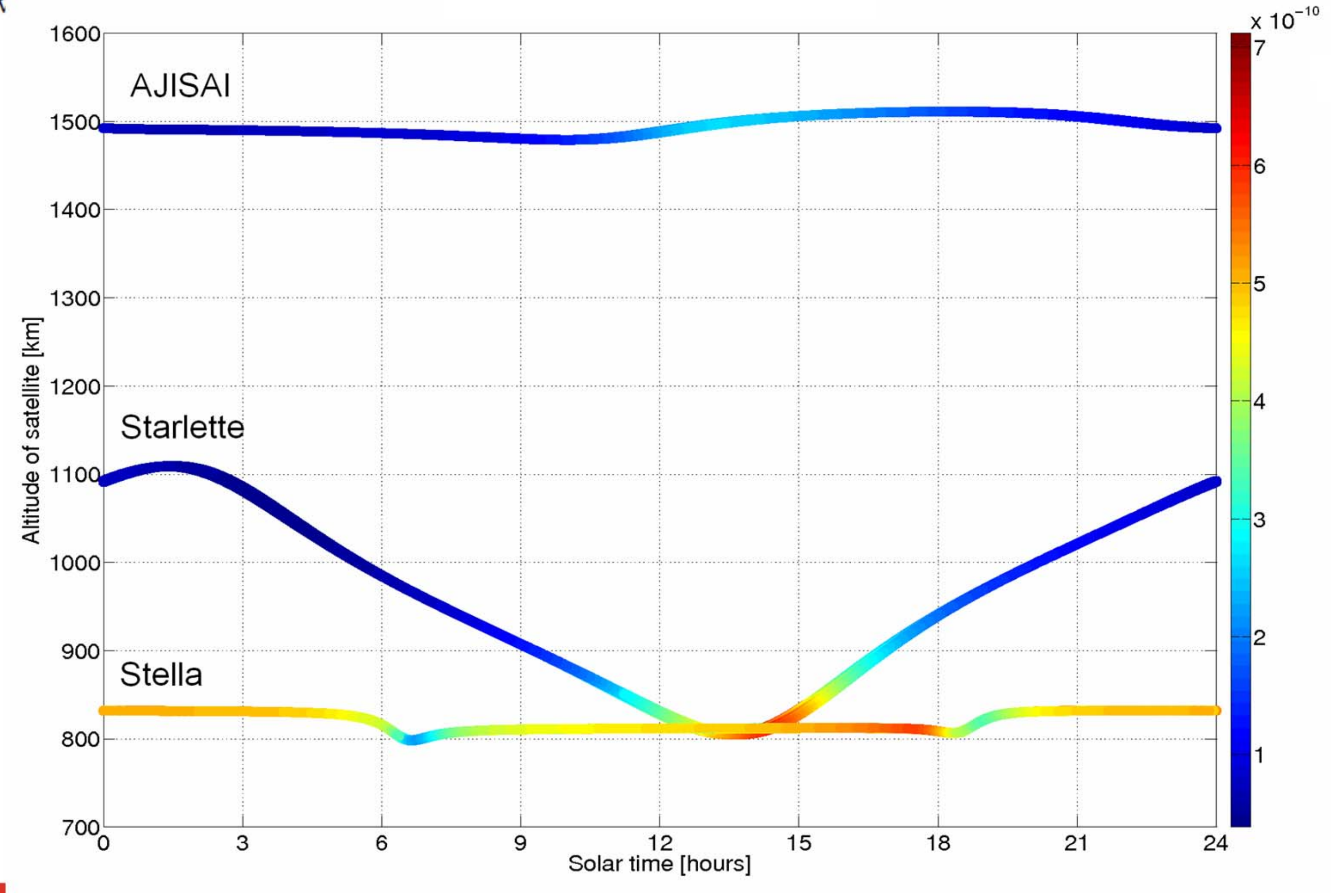
Scale of the reference frame is affected by 0.07 ppb = 0.5 mm

Atmospheric Drag

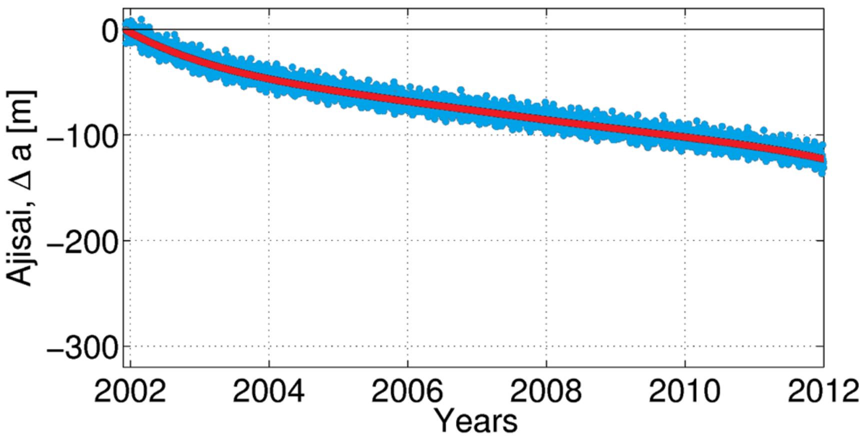
Assuming the laminar air currents, and that the atmosphere is co-rotating with the Earth, and neglecting thermal motion of molecules, the acceleration due to the atmospheric drag can be expressed as (Beutler, 2005):

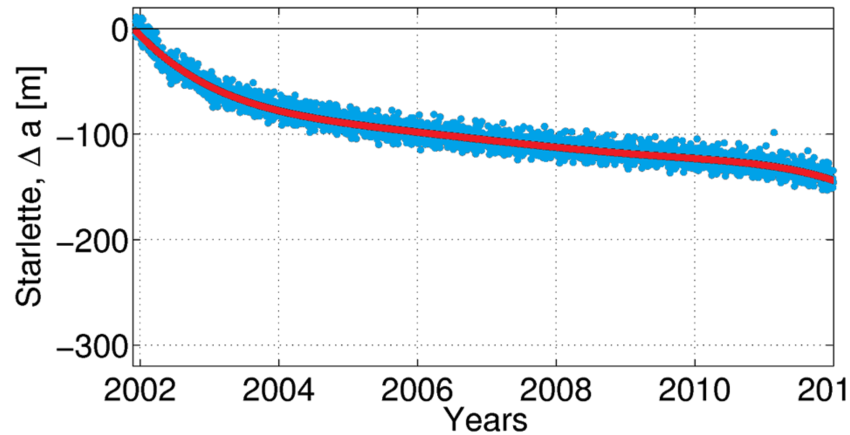
$$\mathbf{a}_D = -\frac{C_D}{2}\,\rho_{(h,T,\lambda,\phi,F_{10.7},A_p)}\,\frac{A}{m}\,\dot{r}'^2\,\frac{\dot{\mathbf{r}}'}{|\dot{r}'|},$$

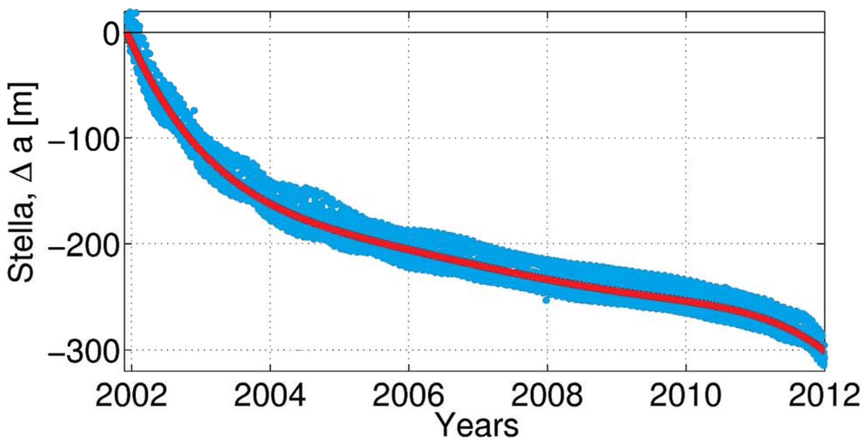
w'



Atmospheric Drag







$$\Delta a = -12 \text{ m/year for AJISAI,}$$

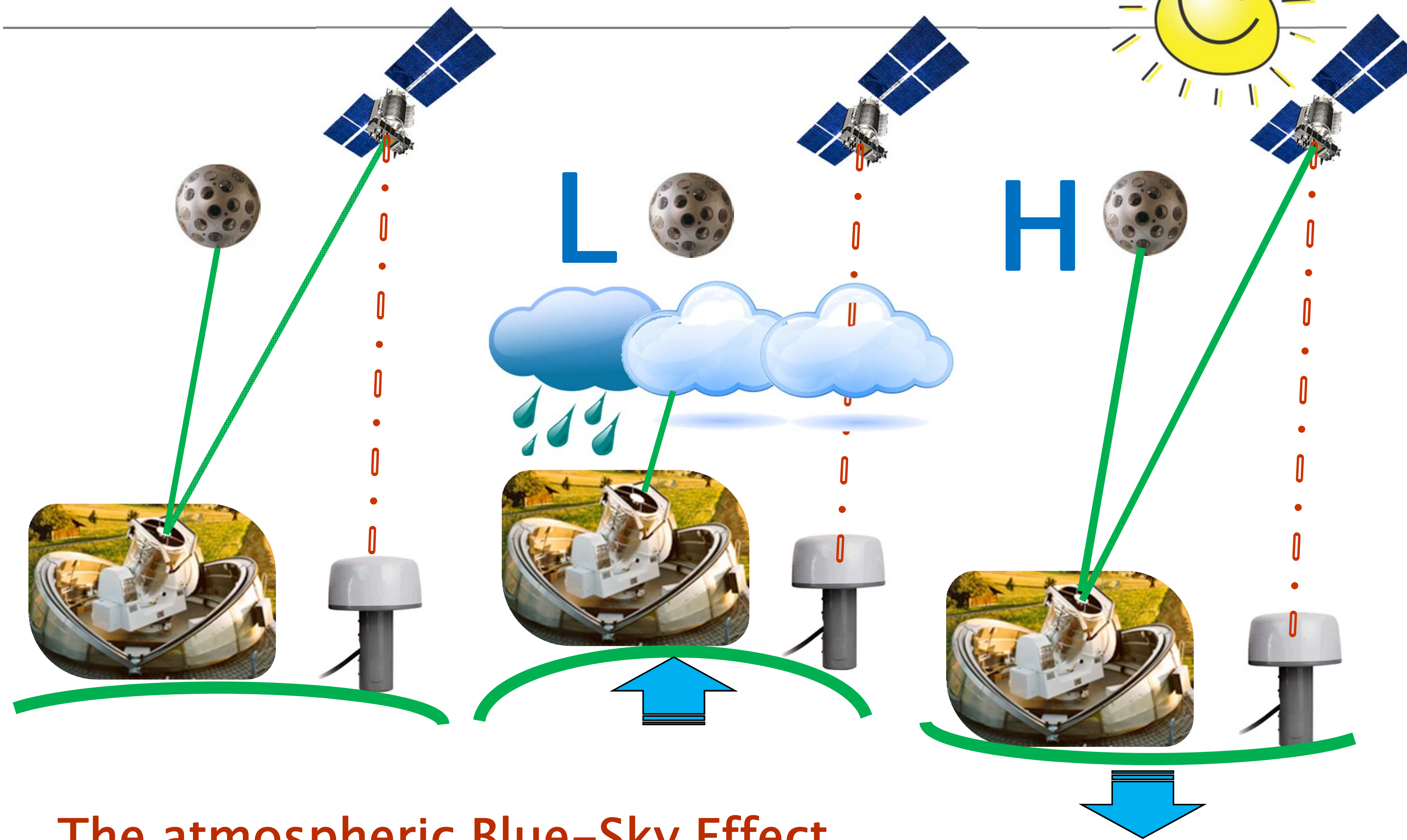
$$\Delta a = -14 \text{ m/year for Starlette,}$$

$$\Delta a = -30 \text{ m/year for Stella.}$$

For LAGEOS-1 and LAGEOS-2 the secular decays of semi-major axes amount to 0.20 m/year and 0.23 m/year, respectively, and are caused by the Yarkovsky and the Yarkovsky-Schach effects.

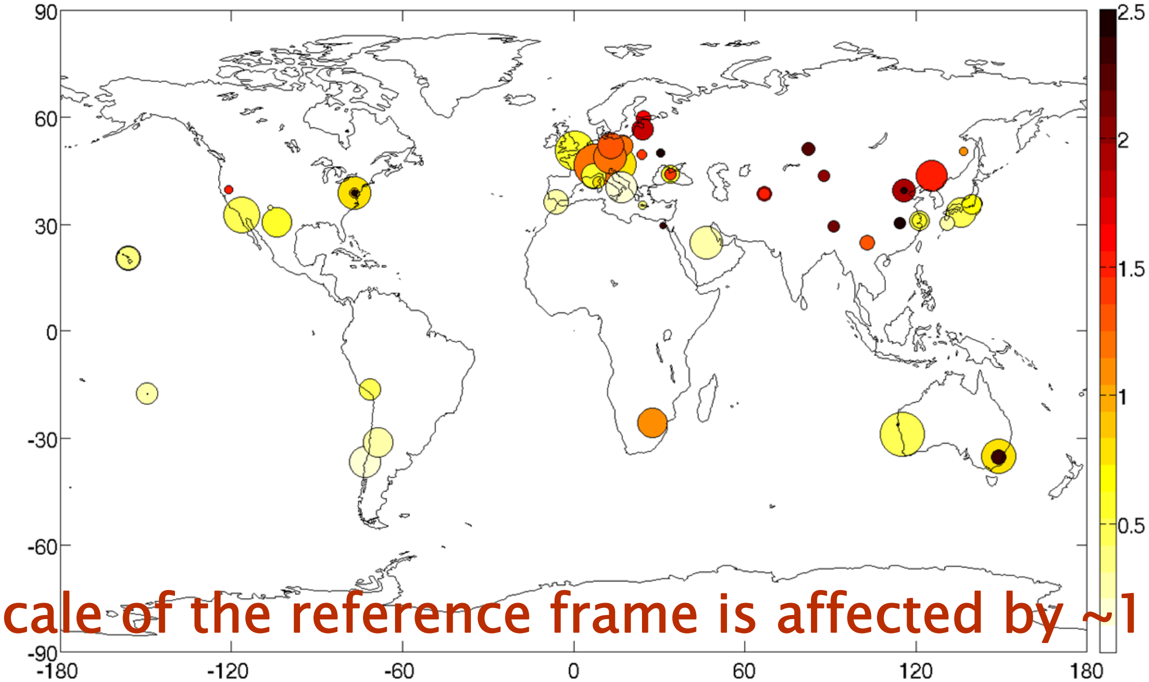
Geodetic parameters:
Station coordinates

Atmospheric Pressure Loading



The atmospheric Blue-Sky Effect

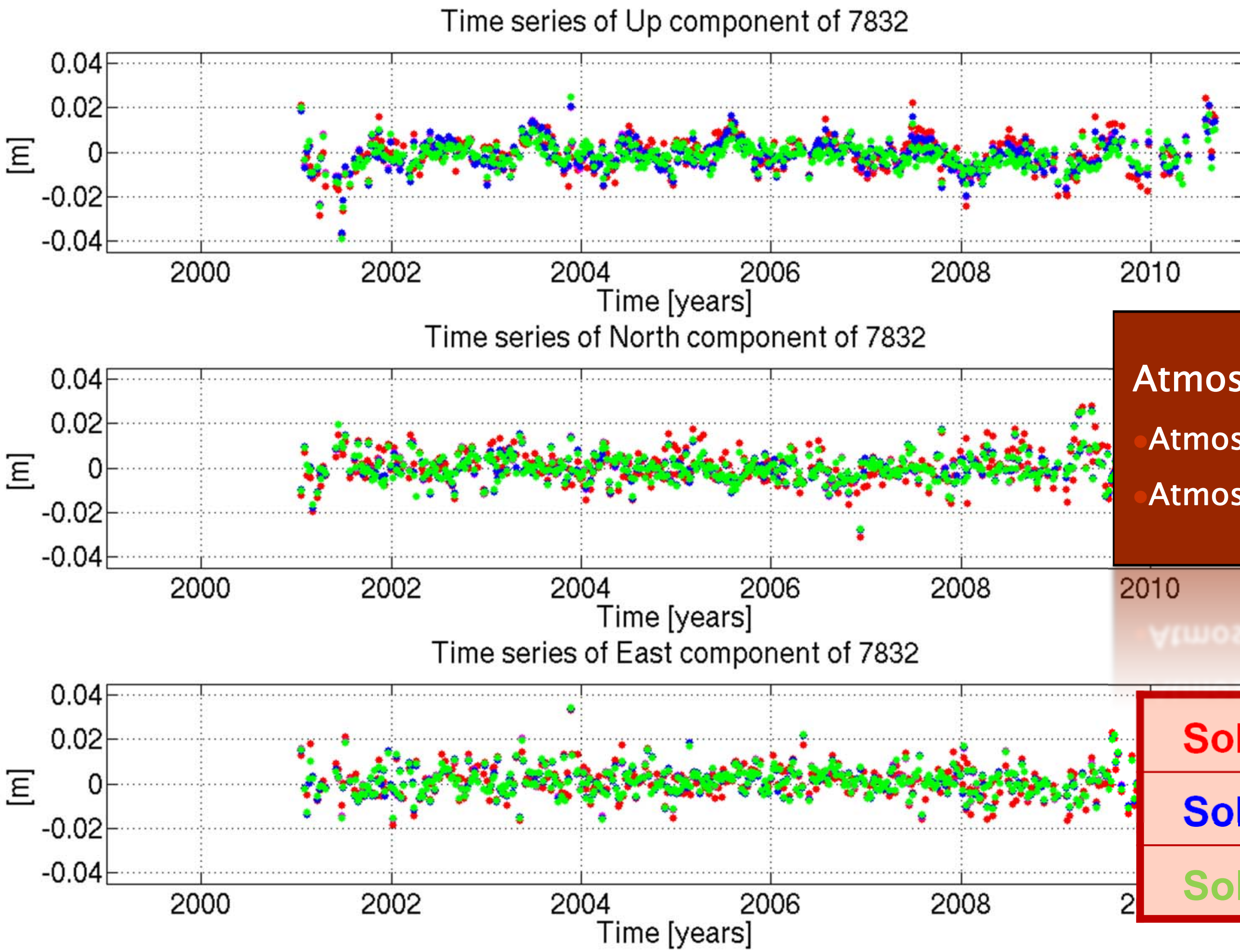
Atmospheric Pressure Loading– the Blue-Sky Effect



Scale of the reference frame is affected by ~1mm

SLR station	Number of normal points (1999–2010)	Mean impact of Atmospheric Pressure Loading	Blue-Sky effect [mm]
Golosiv, Ukraine	330	6.6	4.4
Wuhan, China	1052	4.9	3.2
Beijing-A, China	189	2.7	2.5
Helwan, Egypt	223	3.2	2.4
Altay, Russia	1776	6.7	2.3

Atmospheric Pressure Loading



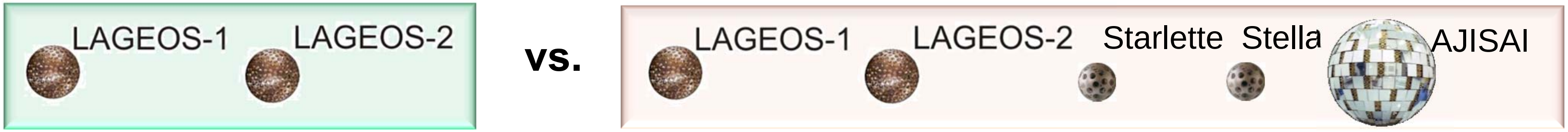
Riyadh, Saudi Arabia

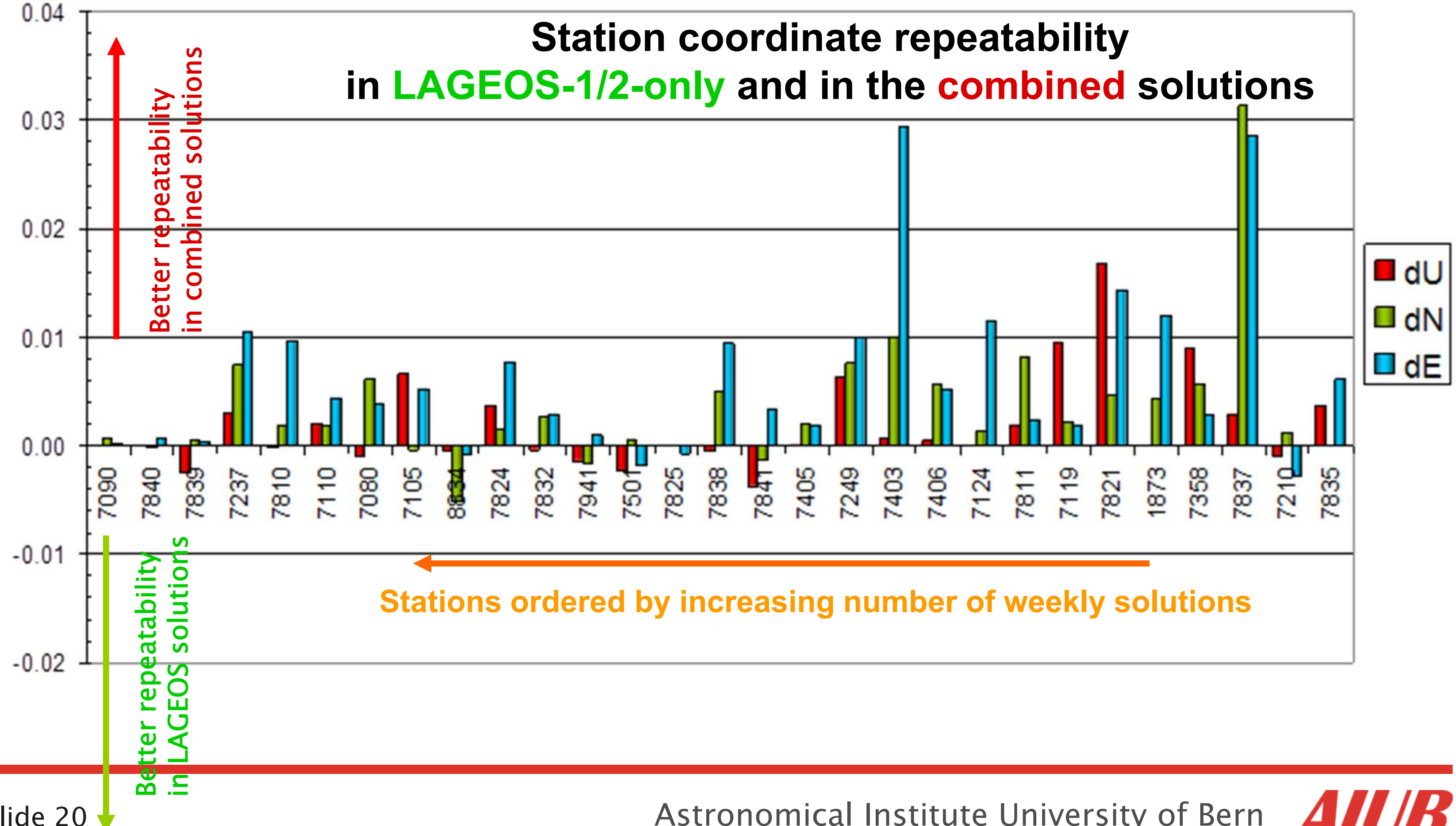
Atmospheric pressure loading:

- Atmospheric tidal loading (ATL)
- Atmospheric non-tidal loading (ANTL)

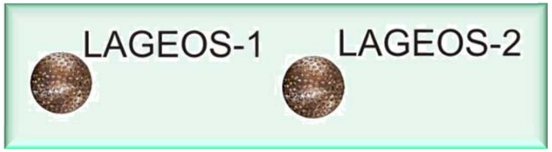
Solution 1	-
Solution 2	ATL
Solution 3	ATL+ANTL

Multi-SLR Satellite Solutions

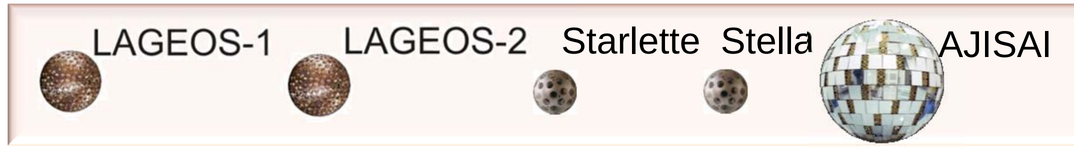




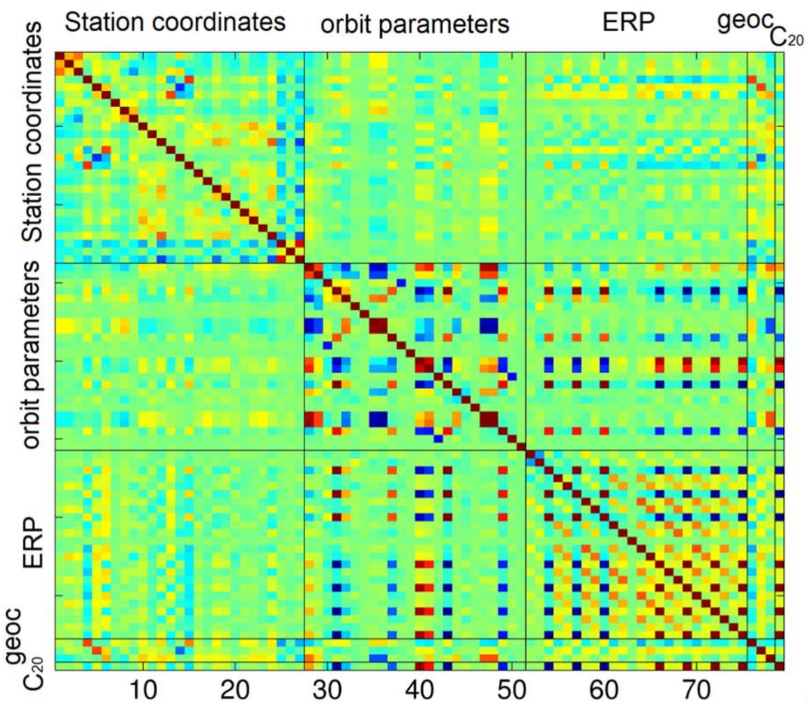
Multi-SLR Satellite Solutions – Correlations



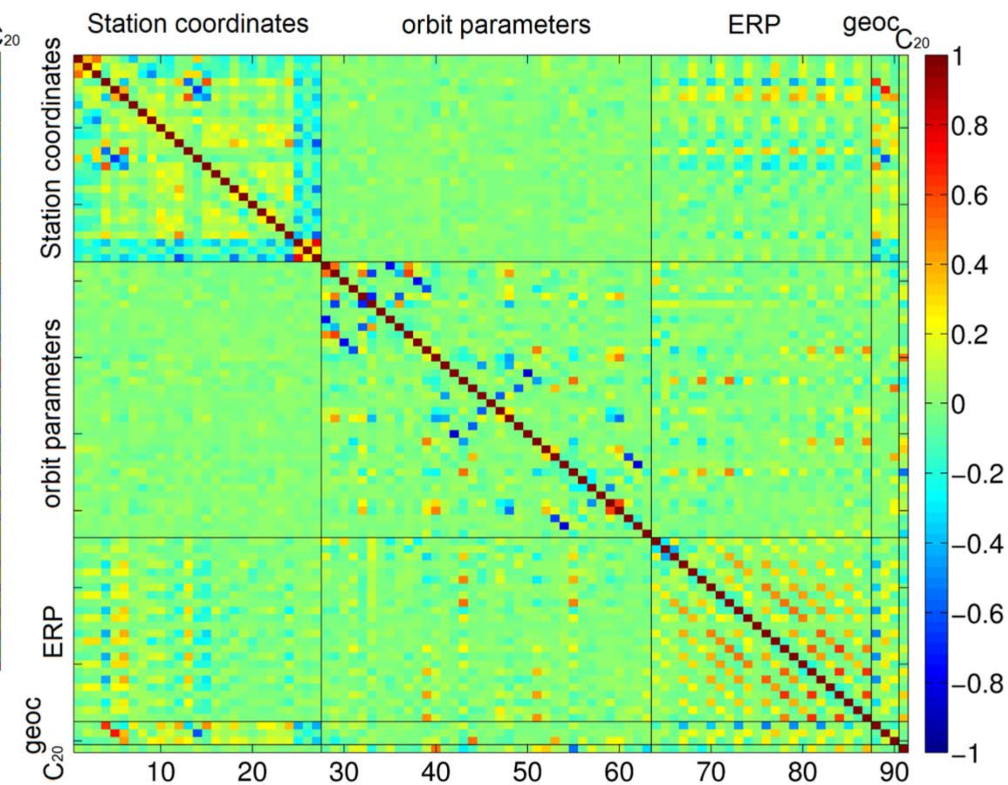
vs.



Correlation matrix

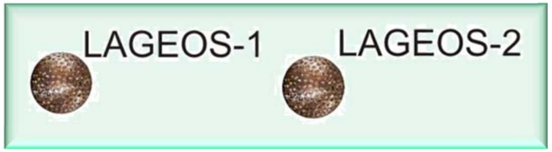


LAGEOS-1/2 solution



LAGEOS-1/2 + AJISAI solution

Multi-SLR Satellite Solutions – Scale



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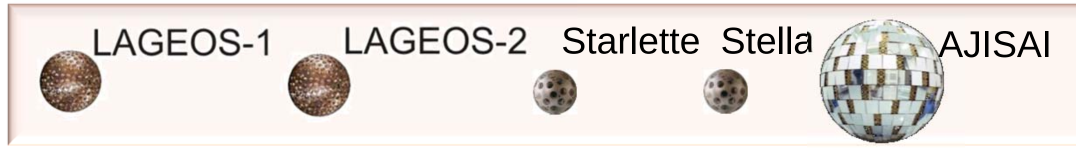
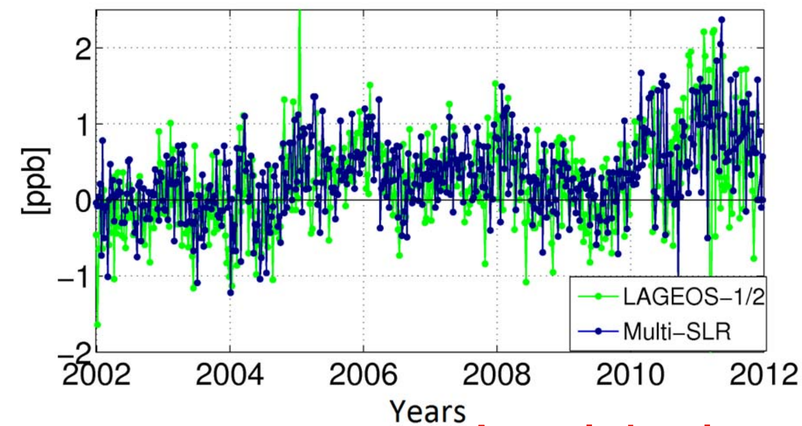


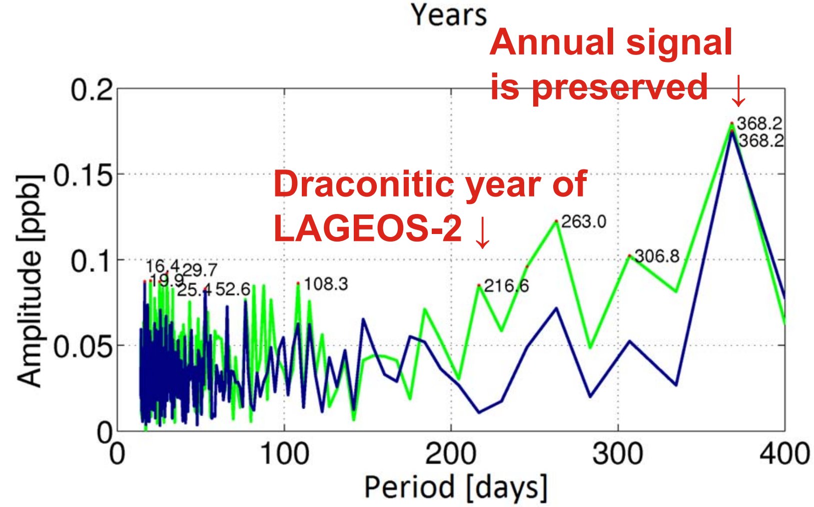
TRF scale estimated from the Helmert 7-parameter transformation of weekly SLR solutions w.r.t. ITRF2008 (SLRF2008).

Orbit modeling deficiencies related to non-gravitational forces appear as the periods of the draconitic year.

Draconitic years of geodetic satellites:

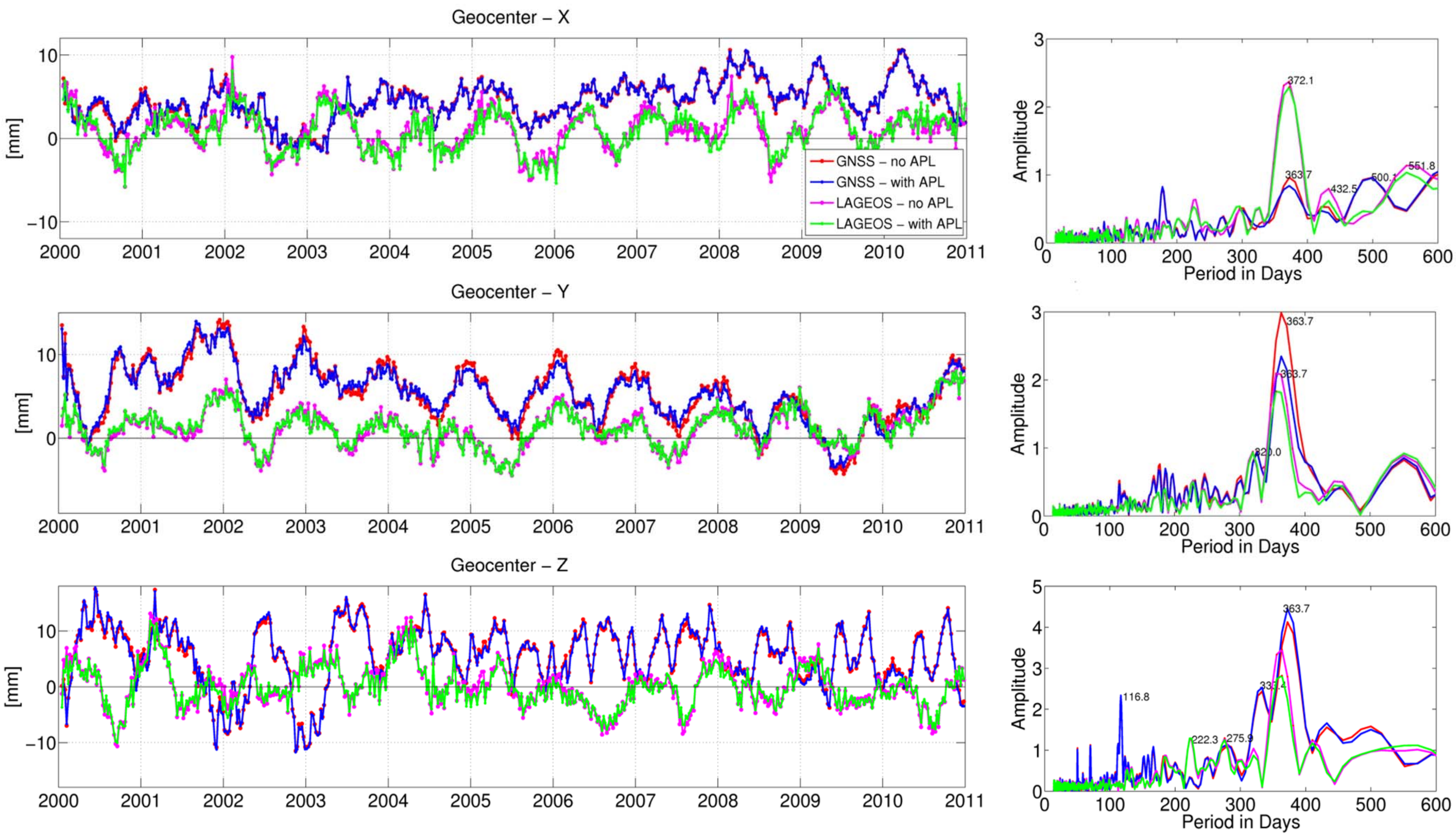
- 222 days: LAGEOS-2,
- 560 days: LAGEOS-1,
- 89 days: AJISAI,
- 73 days: Starlette,
- 182 days: Stella.



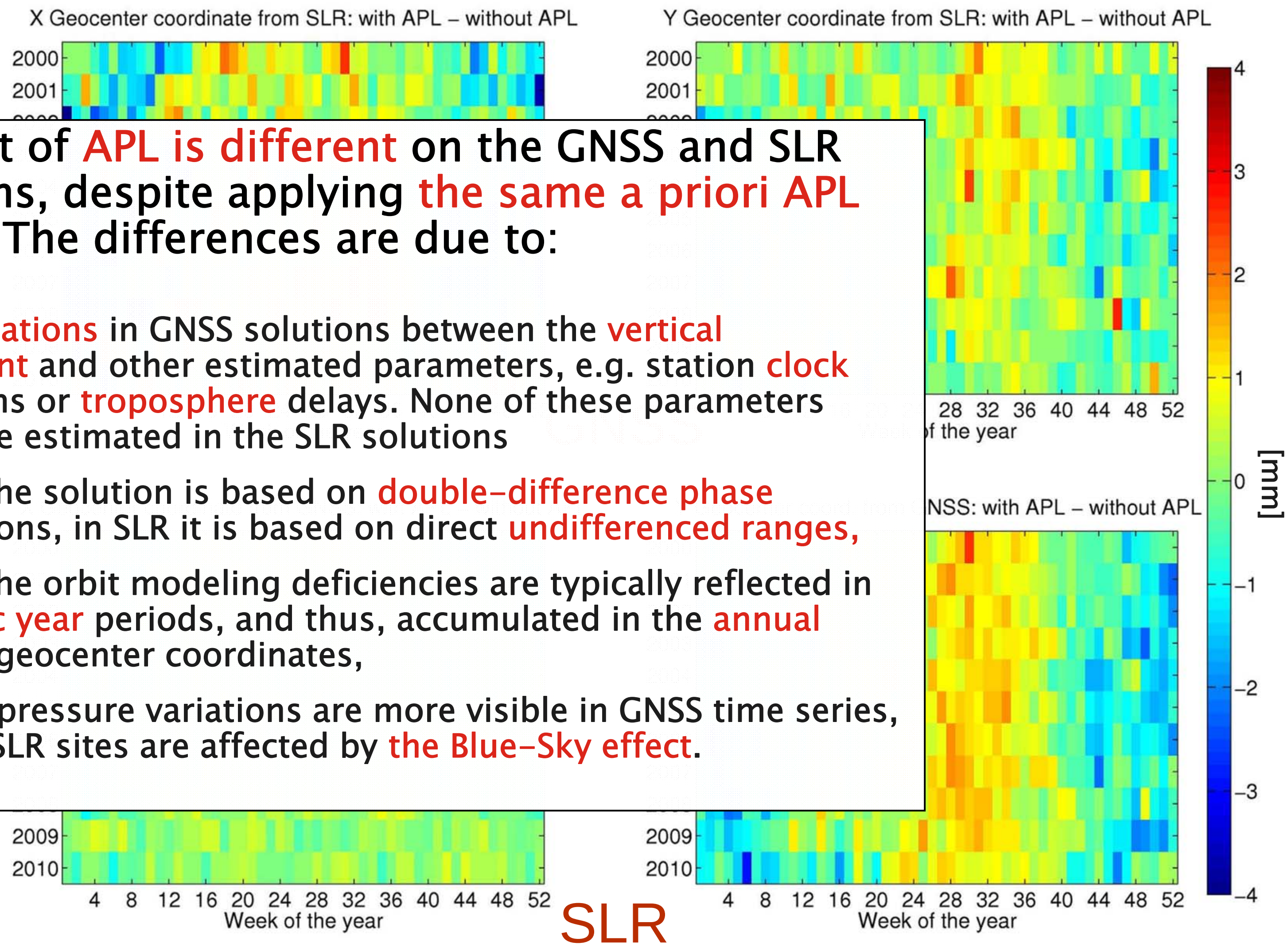


Geodetic parameters:
Geocenter coordinates

Geocenter coordinates from SLR and GNSS



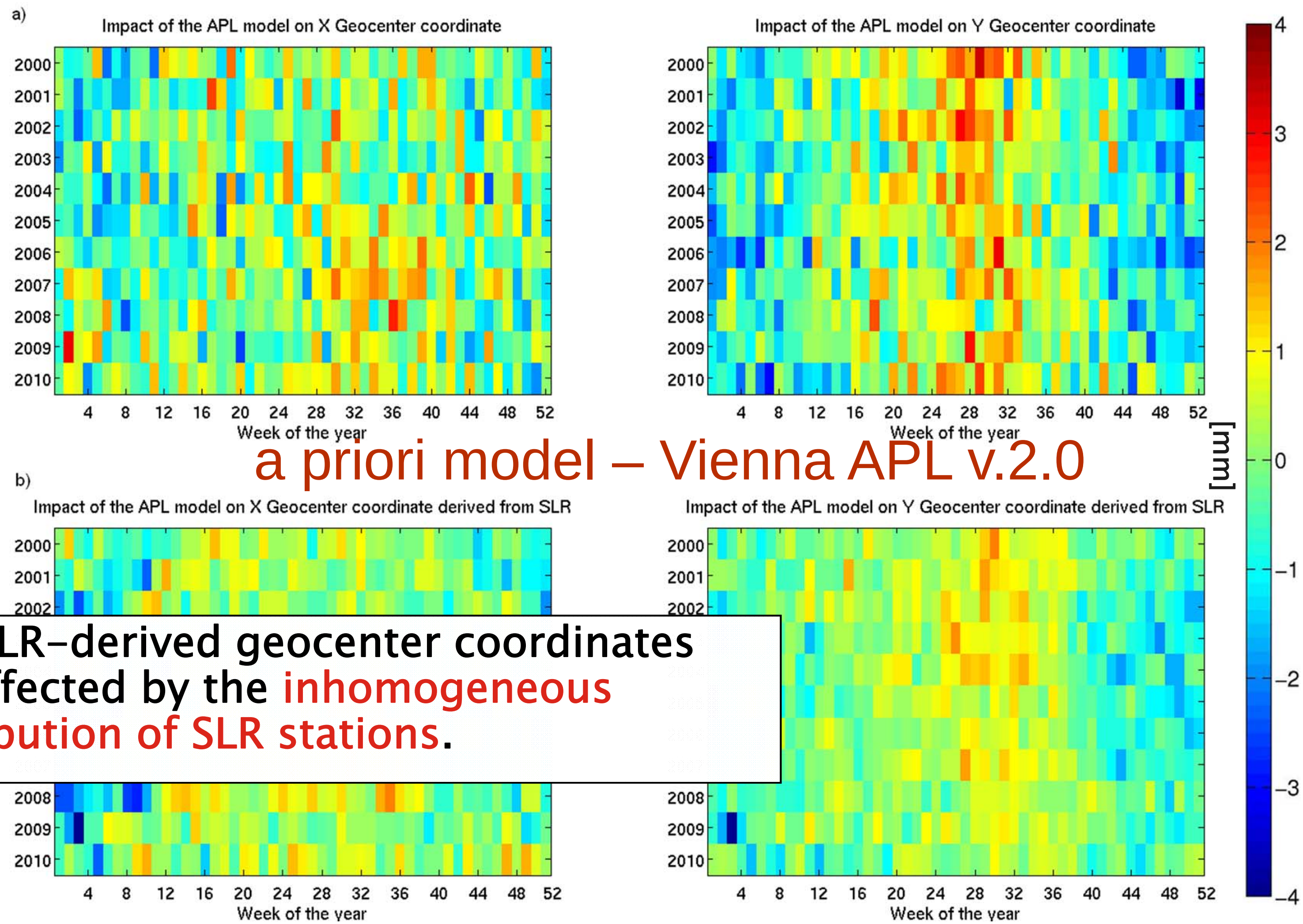
Geocenter coordinates from SLR and GNSS



The impact of APL is different on the GNSS and SLR solutions, despite applying the same a priori APL model. The differences are due to:

- the correlations in GNSS solutions between the vertical component and other estimated parameters, e.g. station clock corrections or troposphere delays. None of these parameters have to be estimated in the SLR solutions
- in GNSS the solution is based on double-difference phase observations, in SLR it is based on direct undifferenced ranges,
- in GNSS the orbit modeling deficiencies are typically reflected in draconitic year periods, and thus, accumulated in the annual signal of geocenter coordinates,
- seasonal pressure variations are more visible in GNSS time series, whereas SLR sites are affected by the Blue-Sky effect.

Geocenter coordinates from SLR and GNSS

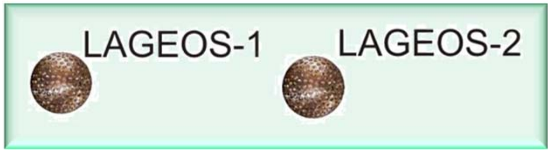


a priori model – Vienna APL v.2.0

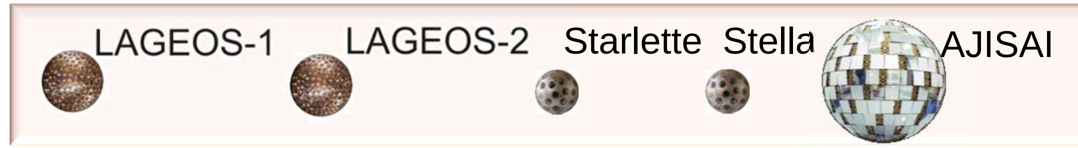
The SLR-derived geocenter coordinates are affected by the inhomogeneous distribution of SLR stations.

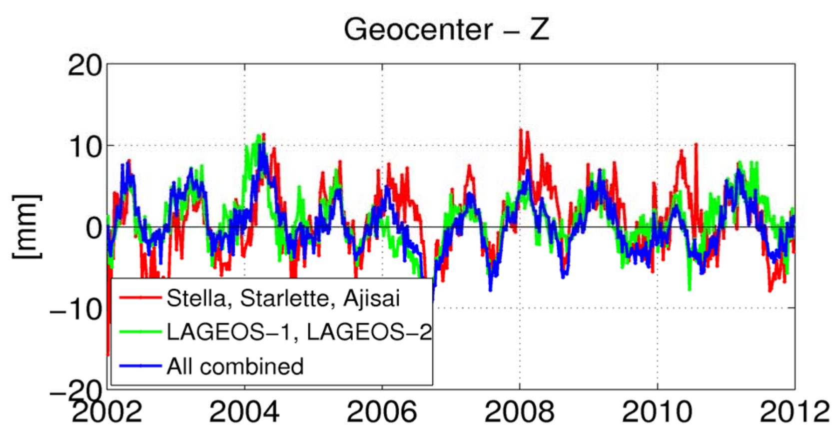
a priori model on the inhomogeneous SLR network

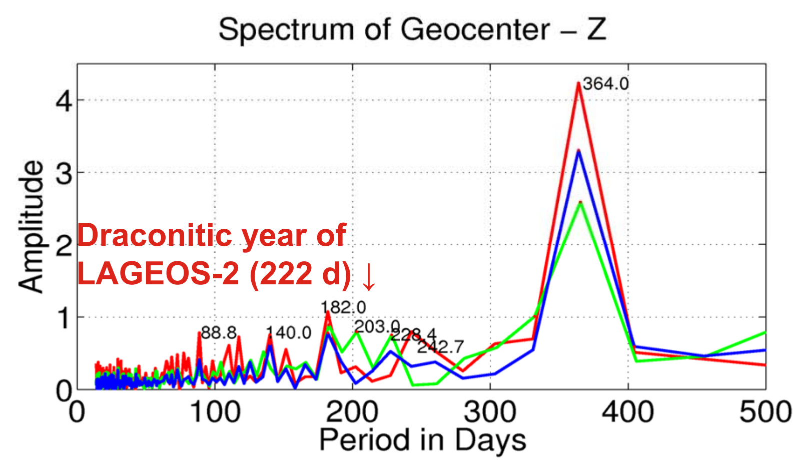
Geocenter coordinates from multi-SLR



vs.



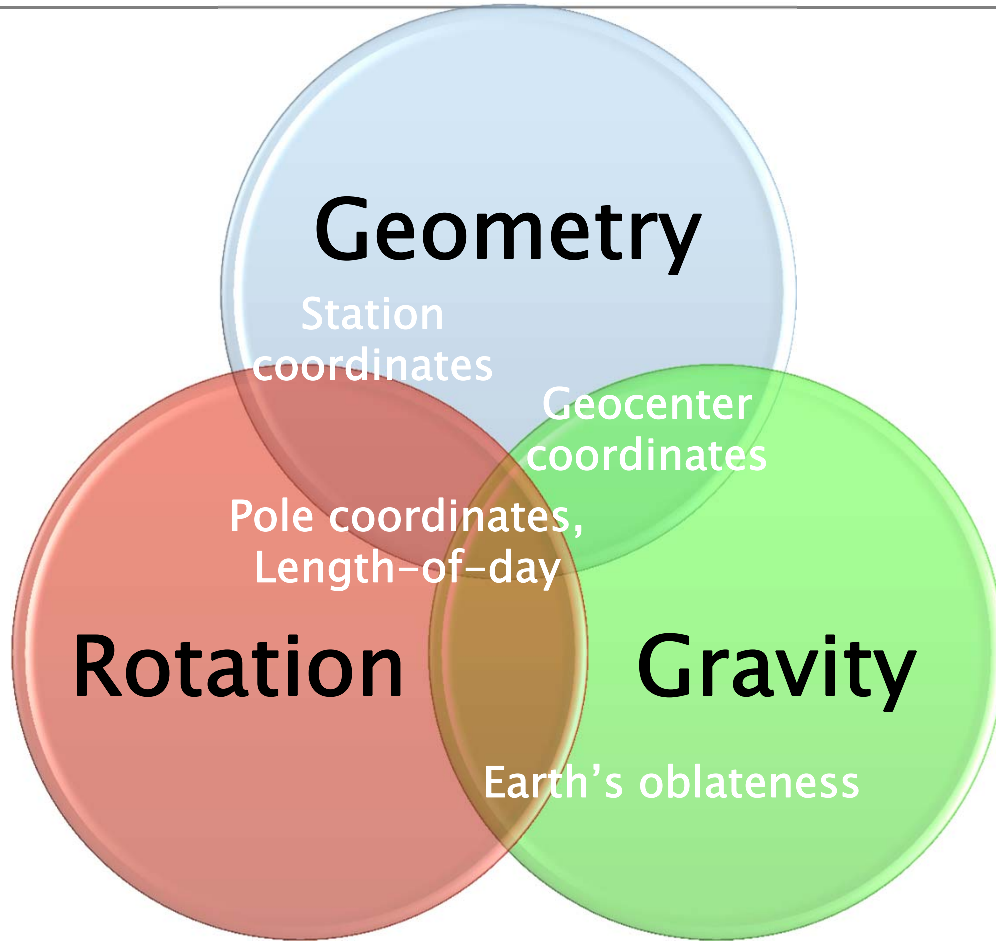




From the analysis of correlations coefficients between the Z geocenter coordinate and the SC orbit parameter, the correlation coefficients are −0.83, and 0.58 for LAGEOS-1, and LAGEOS-2, respectively in LAGEOS-only solutions. These correlations are reduced to −0.23 and 0.15 in the multi-SLR solutions.

Geodetic parameters:
geometry & rotation & gravity

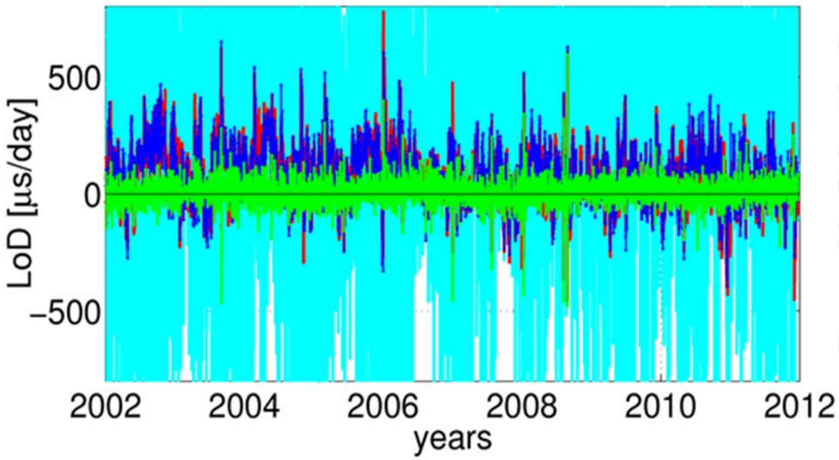
Three pillars of satellite geodesy in one SLR solution

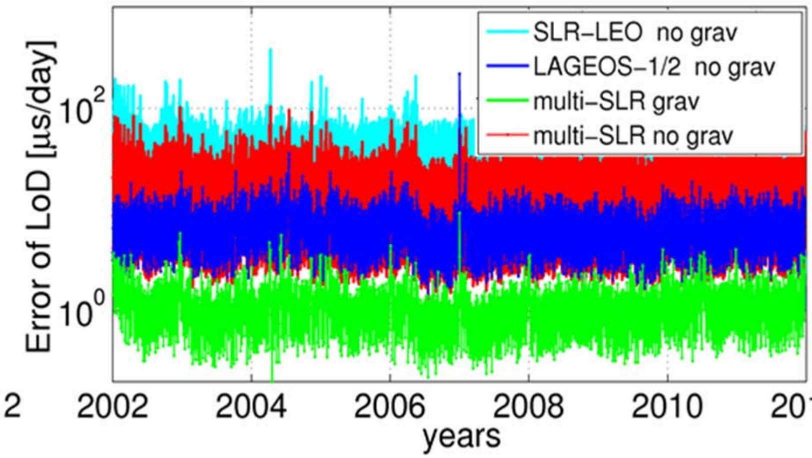


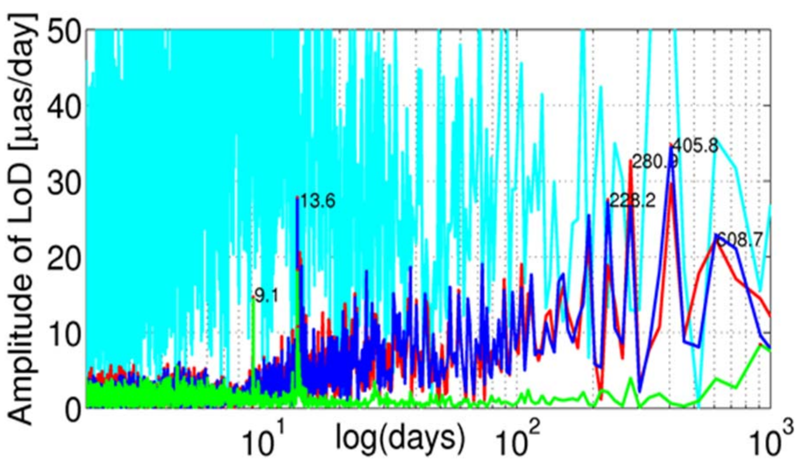
Is it possible to derive simultaneously all three pillars from the combined SLR solution?

Three pillars of satellite geodesy in one SLR solution

LoD w.r.t. C04-08







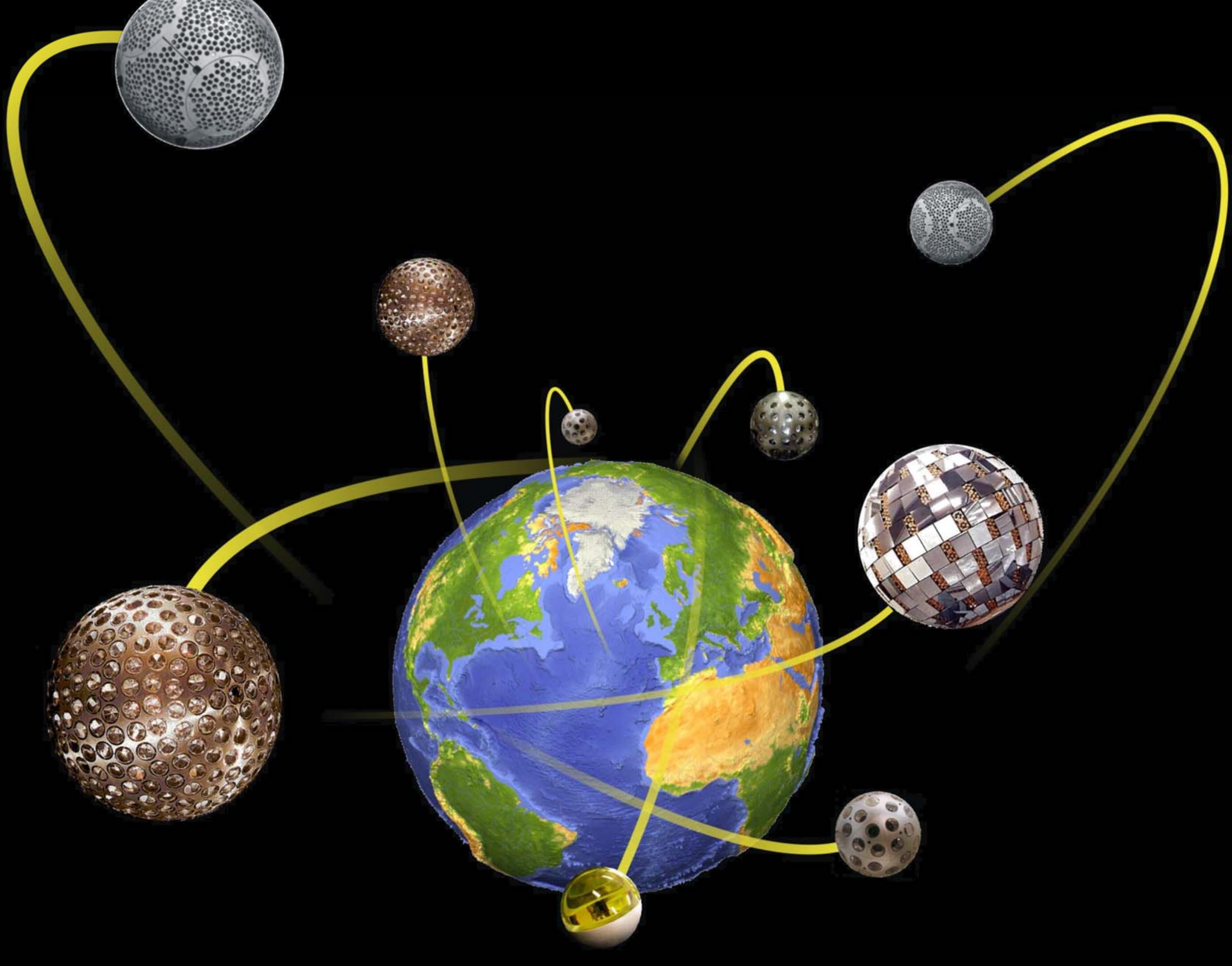
For LoD, the simultaneous estimation of the gravity field parameters:

- 1. reduces the offset of LoD estimates,
- 2. substantially reduces the a posteriori error of estimated LoD. The mean a posteriori error of LoD is 1.3, 16.9, 7.1, and 44.6 µs/day in the multi-SLR solution with gravity, multi-SLR solution without gravity, LAGEOS-1/2 solution without gravity, and SLR-LEO solution without gravity field parameters, respectively.
- 2. reduces peaks in the spectrum analysis, which correspond, e.g., to orbit modeling deficiencies (peaks of 222 days, i.e., a draconitic year of LAGEOS-2, 280 days, i.e., an eclipsing period of LAGEOS-1),

Conclusions

- Appropriate modeling of satellite perturbing forces is crucial for deriving high-accuracy geodetic parameters,
- Solar radiation pressure coefficient for LAGEOS-2 is significantly different from the standard value,
- Appropriate modeling of Atmospheric Pressure Loading reduces the Blue-Sky effect and improves the station coordinate estimates,
- Low orbiting SLR satellites remarkably improve the SLR solutions, e.g., by reducing the correlations between estimated parameters,
- Simultaneous estimation of Earth's Rotation & Geometry & Gravity is feasible and is beneficial in particular for LoD estimates.

Thank you for your attention



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